Journal of Economic Behavior and Organization 6 (1985) 17–53. North-Holland

A BEHAVIORAL MODEL OF THE ECONOMIC LONG WAVE*

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Received May 1983, final version received February 1984

This paper presents a simple model of the economic long wave. The model is based on the System Dynamics National Model. Since 1975 the National Model has provided an increasingly rich theory of the economic long wave. The theory relates capital investment, employment and workforce participation, monetary and fiscal policy, inflation, productivity and innovation, and even political values. The model presented here focuses on capital investment. The structure of the model is shown to be consistent with the principles of bounded rationality. The behavior of the model is analyzed, and capital self-ordering is shown to be sufficient to generate long waves. The model complements the National Model by providing a representation of the dynamic hypothesis that is amenable to formal analysis and is easily extended to include other important mechanisms that may influence the nature of the long wave.

1. Introduction

Recent events have revived interest in the economic long wave, sometimes known as the Kondratiev cycle, a cycle of economic expansion and depression of approximately fifty years duration.[1] Since 1975 the System Dynamics National Model has provided an increasingly rich theory of the long wave [Forrester (1976, 1977, 1979, 1981), Graham and Senge (1980), Senge (1982)]. The core of the theory is the 'self-ordering' of capital by the capital sector of the economy — the dependence of capital-producing industries, in the aggregate, on their own output. But the long-wave theory growing out of the National Model is not monocausal; it relates capital investment, employment and workforce participation, aggregate demand,

*This work is based on a model originally developed in 1979. I am indebted to Dana Meadows, Dennis Meadows, Jørgen Randers, Leif Ervik, and Elizabeth Hicks for assistance with the 1979 version, and to the Gruppen for Ressursstudier, Oslo, for its hospitality. This research was supported in part by the sponsors of the System Dynamics National Model Project. I am indebted to Richard Day and two anonymous reviewers for helpful suggestions. All errors are mine.

[1]Kondratiev (1935) remains the classic of early long-wave research. Van Duijn (1983) provides a comprehensive survey and analysis of long-wave theories and empirical evidence. See also the Aug. and Oct. 1981 *Futures* 13, nos. 4, 5, edited by Christopher Freeman. For innovation theories, see Schumpeter (1939), Mensch (1979), Mensch et al. (1981), Delbeke (1981) and Kleinknecht (1981). Freeman (1979) and Freeman et al. (1982) focus on unemployment and innovation. See Rostow (1975, 1978) and Mandel (1980, 1981) for long-wave theories based on resource scarcity and class struggle, respectively.

0167-2681/85/$3.30

monetary and fiscal policy, inflation, debt, innovation and productivity, and even political values. The advantages of the National Model are its wide boundary and the rich detail in which economic behavior is represented. However, the complexity of the model makes it difficult to explain the dynamic hypothesis underlying the long wave in a simple and convincing manner.

This paper presents a simple model of the economic long wave based on the self-ordering hypothesis. The model demonstrates that self-ordering can account for long waves and isolates the minimum structure sufficient to generate a long wave. In addition, the paper stresses the role of bounded rationality in generating the long wave. It is shown that the decision rules represented in the model for managing production, investment and so on are locally rational. However, in the context of the system as a whole, they produce 'irrational' behavior: periodic over- and underexpansion of the economy.

2. The dynamic hypothesis: Capital self-ordering

Consider the economy divided into two sectors: the capital goods sector and the consumer goods sector. The capital-producing industries of the economy (construction, heavy equipment, steel, mining and other basic industries) supply each other with the capital plant, equipment and materials each needs to operate. Viewed in the aggregate, the capital sector of the economy orders and acquires capital from itself, hence 'self-ordering'.[2]

If the demand for consumer goods and services increases, the consumer-goods industry must expand its capacity and so places orders for new factories, equipment, vehicles, etc. To supply the higher volume of orders, the capital-producing sector must also expand its capital stock and hence places orders for more buildings, machines, rolling stock, trucks, etc., causing the total demand for capital to rise still further, a self-reinforcing spiral of increasing orders, a greater need for expansion, and still more orders.[3]

Fig. 1 shows the basic positive feedback loop created by self-ordering. The strength of the self-ordering feedback depends on a number of factors, but chiefly on the capital intensity (capital/output ratio) of the capital-producing sector. A rough measure of the strength of self-ordering can be calculated by considering how much capital production expands in equilibrium in response

[2]Self-ordering in a two-sector economy can be traced to Frisch's (1933) classic paper. However, Frisch connected self-ordering with a damped 8.5-year cycle, which he believed was kept alive by random shocks such as innovations.

[3]Self-ordering is closely related to the investment accelerator, which is commonly thought to be a factor in the 4- to 7-year business cycle. However, recent work as well as classics such as Metzler (1941) indicate the business cycle revolves around inventory management and suggest the accelerator is primarily involved in longer modes [Forrester (1982), Low (1980), Mass (1975)].

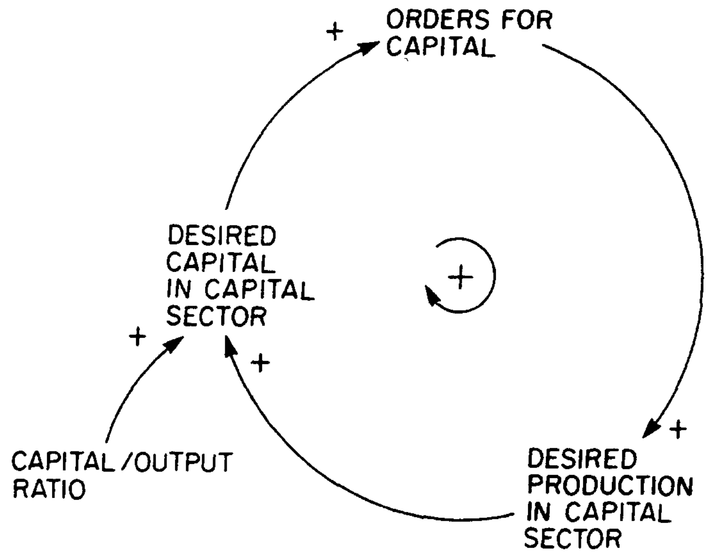

Fig. 1. Basic self-ordering loop.

to an increase in investment in the rest of the economy. It is easily shown that the equilibrium multiplier effect created by self-ordering is given by[4]

$$\text{(i)} \qquad KPR = GINV * \left[1 \Big/ \left(1 - \frac{KCOR}{KALC} \right) \right],$$

where

KPR = capital sector, production (capital units/year),
$KCOR$ = capital sector, capital/output ratio (years),
$KALC$ = capital sector, average life of capital (years),
$GINV$ = goods sector, investment (capital units/year),

Eq. (i) indicates how much capital production must increase in the long run when the investment needs of the rest of the economy rise, taking into account the extra capital needed to maintain the capital sector's own stock at the higher level. Assuming an average life of capital of twenty years and an average capital/output ratio of three years (approximate values for the aggregate economy), the expression above yields a multiplier effect of 1.18. In the long run, an increase in investment in the rest of the economy yields an additional 18% increase in total investment through self-ordering.

[4]Production of capital KPR equals the investment in plant and equipment of the goods sector $GINV$ plus the investment of the capital sector $KINV$, $KPR = GINV + KINV$. In equilibrium, gross investment equals physical depreciation. If the average lifetime of capital $KALC$ (the aggregate of plant and equipment) were twenty years, one-twentieth of the capital stock KC would have to be replaced each year. Thus $KINV = KC/KALC$. The capital stock is related to capital production by the capital/output ratio $KCOR$ (years), $KC = KPR * KCOR$. Substituting for $KINV$ and KC yields eq. (i). Frisch (1933) proves a similar result.

The long wave is an inherently disequilibrium phenomenon, however, and during the transient adjustment to the long run the strength of self-ordering is greater than in equilibrium. As shown in fig. 2, an increase in orders for capital not only increases the steady-state rate of output required, but depletes the inventories and swells the backlogs of the capital sector. To correct the imbalance, firms must expand output above the order rate, causing desired capital to expand still more, further swelling the total demand for capital. Production must remain above orders long enough to restore inventories and backlogs to normal levels. An increase in orders for capital depletes inventories and increases backlogs because production lags behind orders. Production lags orders for several reasons. It takes time for firms to recognize that an unanticipated change in demand is permanent enough to warrant a change in output. And once desired output rises, it takes time to increase employment and especially to increase capacity.

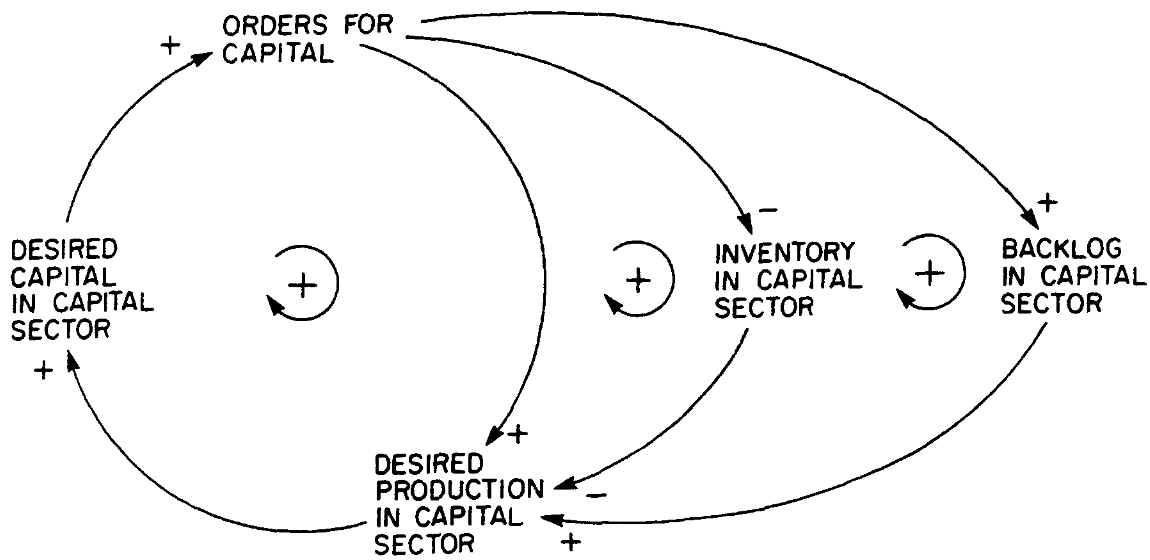

Fig. 2. Amplification added by inventory and backlog adjustments.

The disequilibrium pressures of low inventory and high backlog can significantly amplify the effect of an unanticipated increase in demand, further strengthening the basic self-ordering loop.[5] Other mechanisms create additional amplification. When orders for capital exceed production, delivery times begin to rise. Faced with longer lead times and spot shortages of specialized equipment, firms must hedge by ordering farther ahead and placing orders with more than one supplier, a process described by Thomas W. Mitchell (1923, p. 645):

> 'Retailers find that there is a shortage of merchandise at their sources of supply. Manufacturers inform them that it is with great regret that they

[5]Mass (1980) discusses amplification created by stock-and-flow disequilibrium.

> are able to fill their orders only to the extent of 80 percent; there has been an unaccountable shortage of materials that has prevented them from producing to their full capacity. They hope to be able to give full service next season, by which time, no doubt, these unexplainable conditions will have been remedied. However, retailers, having been disappointed in deliveries and lost 20 percent or more of their possible profits thereby, are not going to be caught that way again. If they want 90 units of an article, they order 100, so as to be sure, each, of getting the 90 in the pro rata share delivered. Probably they are disappointed a second time. Hence they increase the margins of their orders over what they desire, in order that their pro rata shares shall be for each the full 100 percent that he really wants. Furthermore, to make doubly sure, each merchant spreads his orders over more sources of supply.'

The hoarding phenomenon described by Mitchell is quite common, most recently contributing to the gasoline crisis of 1979 [Neff (1982)]. For the aggregate capital sector, ordering farther ahead to compensate for a rising lead time adds to the total demand for capital, causing lead times to rise still further and creating still more pressure to order (fig. 3).

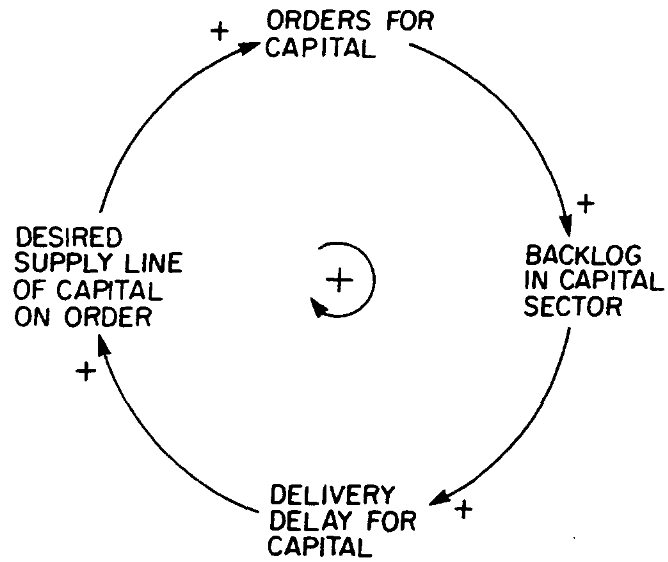

Fig. 3. Rising delivery delays stimulate additional ordering.

According to the theory derived from the National Model, the response of the capital sector to changes in demand is significantly amplified and reinforced by the positive self-ordering loops. An increase in demand for capital leads to a further increase through self-ordering. Once a capital expansion gets under way, the positive loops sustain it until production catches up to orders, excess capital is built up, and orders begin to fall. At that point, the loops reverse. A reduction in orders further reduces investment demand, leading to a contraction in the capital sector's output and to declining employment, wages, aggregate demand and GNP. Capital production must remain below the level required for replacement and long-run growth until the excess physical and financial capital is depreciated — a process that may take a decade or more due to the long lifetimes of plant and equipment. Once the capital stock is worn out, investment rises and triggers the next upswing.[6]

The preceding discussion is not a complete model of the long wave. The National Model includes a broad range of additional amplifying feedbacks. The additional mechanisms involve growth expectations, employment, workforce participation, wages, inflation, interest rates, debt, consumer demand, international trade, innovation, and even political values (see appendix 1).[7] Rather, the relationships above constitute a dynamic hypothesis — the essential feedback structure in the genesis of the long wave. To be a useful hypothesis, self-ordering must be evaluated in a formal model that permits reproducible tests. Further, the relative importance of the various self-ordering loops must be evaluated. The model developed below is used to address these questions:

(1) Is self-ordering sufficient to produce a long wave?
(2) What factors control the period and amplitude of the long wave?
(3) What non-linearities are important in causing the long wave?
(4) How might mechanisms excluded from the model alter its behavior?

3. Behavioral foundations: Bounded rationality

The model is based in part on the theory of bounded rationality [Cyert and March (1963), March (1978), Merton (1936), Nelson and Winter (1982), Simon (1947, 1957, 1978, 1979)]. The essence of the theory is summarized in the principle of bounded rationality, as formulated by Herbert Simon [(1957, p. 198)]:

> 'The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality.'

The theory of bounded rationality is supported by a large and diverse body of empirical research.[8] Bounded rationality has several important implications for behavioral modeling of economic dynamics.

[6]For a more complete description, see Sterman (1982).

[7]See Forrester et al. (1983). On innovation, see the work of Mensch and Freeman. Content analysis of political platforms has documented 50-year cycles in both American and British political values that correspond to the timing of the economic cycle [Namenwirth (1973), Weber (1981)].

[8]Complete references cannot be given here. Excellent discussion and references to the literature can be found in Kahneman et al. (1982) and Hogarth (1980). Morecroft (1983) provides an excellent treatment of the relationships between bounded rationality and system dynamics.

3.1. Limited information-processing capability

Humans have a limited ability to process information. As a consequence, 'perception of information is not comprehensive but *selective*' [Hogarth (1980, p. 4), original emphasis]. For both physiological and psychological reasons, people take only a very few factors or cues into account when making decisions. The cues that are taken into account are not those with the best predictive ability. Rather, people focus on cues they judge to be relatively certain, systematically excluding uncertain or remote information regardless of its importance [Hogarth (1980, p. 36), Kahneman et al. (1982, esp. ch. 4, 7–10)]. Additionally, 'people give more weight to data that they consider *causally related to a target object*...' and therefore focus on cues they believe to be meaningful [Hogarth (1980, pp. 42–43), emphasis in original]. However, precisely because of limited information-processing capability and the aversion to uncertainty, people are notoriously poor judges of causality and correlation, and in controlled experiments systematically create mental models at variance with the known situation.[9] Ironically, most people, including many professionally trained in statistics, consistently assert that their own performances are immune from such pitfalls, are reluctant to abandon their mental models, and selectively use hindsight to 'validate' their preconceptions.[10]

3.2. Decentralized decisionmaking

Limited information-processing ability forces people to divide the total task of managing an organization into smaller units. By establishing subgoals assigned to subunits within the organization, the complexity of the total problem is vastly reduced. The subunits ignore, or treat as exogenous, those aspects of the total situation that are not directly related to their subgoal [Simon (1947, p. 79)]:

> 'Individual choice takes place in an environment of "givens" — premises that are accepted by the subject as bases for his choice...'.

Besides ignoring much of the information potentially available, people within organizational subunits use simple heuristics or rules of thumb to process information. Rules of thumb rely on relatively certain information that is locally available to the subunit. 'Rules of thumb process information in a straightforward manner, recognizing the computational limits of normal human decision makers under pressure of time' [Morecroft (1983, p. 133)].

[9] Hogarth (1980) discusses numerous separate sources of bias in decisionmaking. Among the common fallacies of causal attribution are the gambler's fallacy and the regression fallacy. [Tversky and Kahneman (1974)].

[10] See Kahneman et al. (1982, esp. chs. 2, 9, 12, 20 and 23). Goffman's (1959) 'dramaturgic' model of public behavior is relevant here: people constantly adjust their public performances so as to enhance their status and competence in the eyes of others.

3.3. Relevance of bounded rationality

The relevance of bounded rationality to the present work is twofold. First, behavioral models in economics are often criticized because they assume people rely on decisionmaking heuristics, 'irrationally' failing to optimize their performance. Performance, it is argued, could be improved by using more information or more sophisticated decision rules. But a behavioral model is descriptive not normative: to simulate (in the sense of mimic) the behavior of a system accurately, decisionmaking must be portrayed as it is and not as it might be if people were omniscient optimizers. The empirical work on decisionmaking heuristics and cognitive biases provides a firm empirical foundation for behavioral models in economics.

Second, behavioral models are often criticized as ad hoc — without the criterion of objective rationality, how can the appropriateness of any particular decision rule be judged? In addition to direct observation of the decisionmaking process, bounded rationality provides such a criterion: the local or intended rationality of the decision rules. A decision rule is locally rational if it would produce rational behavior were the actual environment as simple as the decisionmaker presumes, that is, if the 'premises accepted by the subject' were true.

4. The model

The model represents a simplified generic firm or sector of the economy (the 'production sector').[11]

4.1. Production and capacity utilization

$$PR_t = PC_t * CU_t, \tag{1}$$

$$CU_t = f_1(IP_t/PC_t), \qquad f_1(0)=0, \quad f_1(1)=1, \quad f_1' \geqq 0, \quad f_1'' \leqq 0, \tag{2}$$

$$IP_t = B_t/NDD, \tag{3}$$

where

PR = production rate (units/year),
PC = production capacity (units/year),
CU = capacity utilization (fraction),
IP = indicated production (units/year),
B = backlog of unfilled orders (units),
NDD = normal delivery delay (years).

[11]The model is formulated in continuous time as a set of integral equations, and was simulated using Euler integration (see appendix 2).

Production is determined by production capacity and the rate of capacity utilization. Capacity utilization is determined by the ratio of indicated production to production capacity. Indicated production is the rate of production required to deliver an order in the normal delivery delay. The normal delivery delay is the time required, in equilibrium, to process, produce and deliver an order.

As shown in fig. 4, capacity utilization varies non-linearly with the ratio *IP/PC*. When $IP/PC > 1$, the rate of production required to meet the normal delivery delay exceeds capacity, which becomes a binding constraint on production. If indicated production drops below capacity, however, output is curtailed. (Inventories are not represented. Production and shipments are therefore always equal, and, if there are no orders to be filled, production must decline to zero.) When desired production is only slightly less than capacity, firms are assumed to reduce utilization only slightly, preferring to maintain relatively full utilization (and hence revenues) by drawing down their backlogs. Delivery delays would become somewhat shorter than normal. If backlog continued to fall, utilization would be gradually cut back until firms were producing at the minimum delivery delay. Further declines in backlog then force proportional reductions in output.[12] The behavior

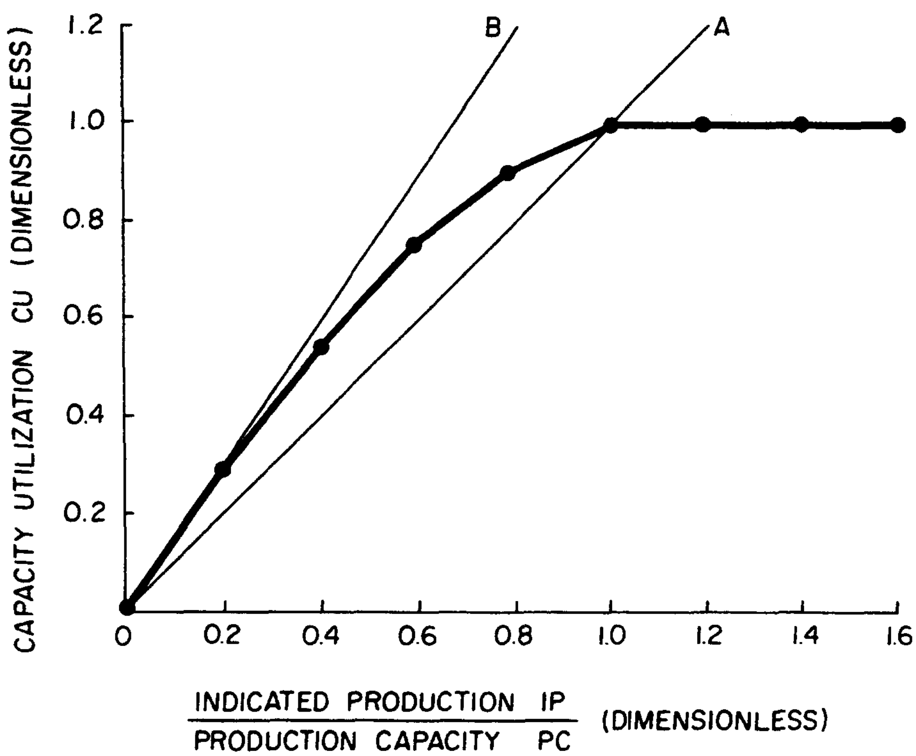

Fig. 4. Capacity utilization.

[12]If firms wanted to maintain the normal delivery delay regardless of capacity, capacity utilization would fall in proportion to the decline in demand, production would equal indicated production, and *CU* would lie along line *A* in fig. 4. If firms wanted to continue to operate at

described by the capacity utilization formulation was illustrated by the machine tool industry during the 1982 recession [*Business Week* (14 March 1982, p. 20)]:

> 'Bad as they are, shipments are outpacing orders by a very wide margin, forcing a continued rundown in the industry's order backlog.... At the average shipment rate of the past three months, backlogs provide less than six months of production, in an industry that had a one-year backlog when the recession began... the low level of capacity utilization suggests that shipments will run ahead of orders well into summer.'

4.2. Production capacity

$$PC_t = C_t/COR. \tag{4}$$

Production capacity PC is determined by capital stock C and the capital/output ratio COR. For simplicity, capital is the only explicit factor of production and the capital/output ratio is assumed to be constant.[13]

$$C_t = \int_{t_0}^{t} (CA_t - CD_t)\,\mathrm{d}t + C_{t_0}, \tag{5}$$

$$CD_t = C_t/ALC, \tag{6}$$

where

CA = capital acquisitions (capital units/year),
CD = capital discards (capital units/year),
ALC = average lifetime of capital (years).

Capital stock, representing both plant and equipment, is the accumulation of capital acquisitions CA less capital discards CD. The simplest formulation

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full capacity at all times, even in the face of diminished demand, utilization would fall only when the sector was producing at the minimum delivery delay, defined by line B. Line B determines the minimum delivery delay because the actual delivery delay or average residence time of an order in the backlog is given by $DD = B/PR = B/(PC*CU)$. When $CU = b*(IP/PC)$ [for $b > 1$ and $b*(IP/PC) \leqq 1$, i.e., when CU lies along line B] $DD = B/(PC*b(IP/PC)) = B/(b*IP)$. But $IP = B/NDD$, so $DD = B/(b*B/NDD) = NDD/b = MDD$ where MDD = Minimum delivery delay (years).

[13] Though a more complete model would include a more sophisticated production function with both variable labor and a variable work week, the dynamics of labor acquisition are primarily associated with the short-term business cycle (see note 3). However, since rising wages contribute to the strength of self-ordering during a long-wave expansion [Forrester et al. (1983)] omission of labor as an explicit factor is likely to reduce the model's ability to generate a long wave. For a dynamic model with multiple factors of production that conforms to the principles of bounded rationality, see Sterman (1981, 1983a).

for capital discards is to assume all units have an equal probability of being discarded regardless of age, defining (in equilibrium) an exponential probability density for the age of individual units, with the mean physical life given by the average life of capital ALC. For simplicity, the average lifetime is assumed constant.[14]

$$CA_t = SL_t/CAT_t, \tag{7}$$

$$SL_t = \int_{t_0}^{t} (CO_t - CA_t)\,\mathrm{d}t + SL_{t_0}, \tag{8}$$

where

SL = supply line of unfilled orders for capital (capital units),
CAT = capital acquisition time (years),
CO = capital orders (capital units/year).

Capital acquisition, or gross investment, is determined by the sector's supply line (the backlog of unfilled orders for capital) and the average delay in acquiring those orders. The capital acquisition time includes the time required for construction. The sector's supply line is augmented as orders for capital are placed with suppliers, and diminished when construction is completed and the capital enters the productive stock of the sector.

4.3. Orders for capital

$$CO_t = C_t * COF_t, \tag{9}$$

$$COF_t = f_2(ICOF_t), \qquad f'_2 \geqq 0, \tag{10}$$

$$ICOF_t = (CD_t + CC_t + CSL_t)/C_t, \tag{11}$$

where

COF = capital order fraction (fraction/year),
$ICOF$ = indicated capital order fraction (fraction/year),
CC = correction to orders from capital stock (capital units/year),
CSL = correction to orders from supply line (capital units/year).

Three motivations for ordering capital are assumed: first, to replace discards; second, to correct any discrepancy between the desired and actual capital stock; and third, to correct any discrepancy between the desired and actual

[14]Sterman (1980) contrasts the lumped capital stock used here to a model with capital disaggregated by vintage. A more complete model would also include a variable average lifetime to represent variations in the discard rate.

supply line.[15] The sum of these three pressures, as a fraction of the existing capital stock, defines the indicated capital order fraction *ICOF*. The actual order fraction *COF* is a non-linear function of the indicated order fraction. For indicated order fractions between 5%/year and 25%/year, $COF = ICOF$. In extreme circumstances, however, the indicated capital order fraction may take on unreasonable values. For example, an extreme excess of capacity could cause *ICOF* to be negative. But since gross investment must be positive, *COF* asymptotically approaches zero as *ICOF* drops below 5% /year. Similarly, to prevent the order fraction from taking on unreasonably large values, it is assumed that the maximum capital order fraction is 30% /year. The limit reflects physical constraints to rapid expansion such as labor and materials bottlenecks, financial constraints, and organizational pressures.[16]

$$CSL_t = (DSL_t - SL_t)/TASL, \tag{12}$$

$$DSL_t = CD_t * PCAT_t, \tag{13}$$

$$PCAT_t = CAT_t, \tag{14}$$

where

DSL = desired supply line (capital units),
TASL = time to adjust supply line (years),
PCAT = perceived capital acquisition time (years).

Firms strive to eliminate discrepancies between the desired and actual supply lines within the time to adjust supply line *TASL*. To ensure an appropriate acquisition rate, firms must maintain a supply line proportional to the delay they face in acquiring capital. As described by Mitchell (1923), if the acquisition time rises, firms must plan for and order new capital farther ahead, increasing the required supply line. The desired supply line is based on relatively certain information — the discard rate and the capital acquisition time perceived by the firm. For simplicity, the perceived capital acquisition time is assumed to equal the actual acquisition time.

[15]Investment resulting from growth expectations would have to be included in a more complete model. The investment function of the model is a simplified version of the System Dynamics National Model investment function. Senge (1978, 1980) shows the SDNM function reduces to the neoclassical investment function [e.g., Jorgenson (1963), Jorgenson et al. (1970)] when a variety of equilibrium and perfect information assumptions are made. The SDNM function is shown to provide a better statistical fit of investment data and to behave more plausibly than the neoclassical function when faced with various test inputs.

[16]The formulation for *COF* excludes order cancellations. Disallowing cancellations is a simplifying assumption. A more complete model would disaggregate unfilled orders from units under construction and would represent cancellations explicitly [Sterman (1981)]. The formulation for *COF* smoothly approaches zero due to the aggregation of firms, some of which will be ordering non-zero amounts even when the average $ICOF < 0$.

$$CC_t = (DC_t - C_t)/TAC, \tag{15}$$

$$DC_t = RC * f_3(IC_t/RC), \qquad f_3(0) = 0, \quad f_3(1) = 1, \quad f'_3 \geqq 0, \quad f''_3 \leqq 0, \tag{16}$$

$$IC_t = IPC_t * COR, \tag{17}$$

where

DC = desired capital (capital units),
TAC = time to adjust capital (years),
RC = reference capital (capital units),
IC = indicated capital (capital units),
IPC = indicated production capacity (units/year).

Like the supply line correction, firms attempt to correct discrepancies between desired and actual capital stock over a period of time given by the time to adjust capital. Desired capital is non-linearly related to the indicated capital stock, which is the stock needed to provide the indicated production capacity IPC. (Indicated production capacity is the capacity judged necessary to meet expected demand.) Diminishing returns to capital are assumed to limit capital expansion when IC becomes large relative to the initial equilibrium capital stock RC.[17]

4.4. Desired capacity

$$IPC_t = EO_t + CB_t, \tag{18}$$

$$CB_t = (B_t - IB_t)/TAB, \tag{19}$$

$$IB_t = NDD * EO_t, \tag{20}$$

where

EO = expected orders (units/year),
CB = correction from backlog (units/year),
IB = indicated backlog (units),
TAB = time to adjust backlog (years).

Indicated production capacity reflects the capacity the sector judges necessary both to fill expected orders and adjust the backlog of unfilled orders to an appropriate level. The speed with which the sector strives to correct discrepancies between the actual and indicated backlog is determined

[17] It is assumed that employment can be expanded in proportion to capital as IC begins to exceed RC. As the available labor supply is exhausted, however, expansion of capital lowers the marginal productivity of capital and diminishes incentives for further expansion even if demand remains high.

by the time to adjust backlog. TAB represents management's sensitivity to abnormal delivery delays. Indicated backlog is the backlog required to fill the expected order rate within the normal delivery delay.

$$EO_t = \int_{t_0}^{t} \frac{(OR_t - EO_t)}{TAO} \mathrm{d}t + EO_{t_0}, \tag{21}$$

where TAO = time to average orders (years).

The expected order rate represents the sector's forecast of demand, conditional on available information and the rules of thumb for forecasting used by the sector. The firm is assumed to forecast demand by averaging past orders. Orders are smoothed because it takes time for firms to decide that an unanticipated change in demand is lasting enough to warrant capacity expansion. Smoothing filters out short-term noise in demand, providing a more certain measure of long-run demand than the raw order rate and preventing wild swings in investment by allowing the backlog to buffer the system from the short-term variability of demand. First-order exponential smoothing is assumed for the averaging process. The smoothing time is given by the time to average orders TAO.[18]

$$DD_t = B_t/PR_t, \tag{22}$$

$$B_t = \int_{t_0}^{t} (OR_t - PR_t)\,\mathrm{d}t + B_{t_0}, \tag{23}$$

$$OR_t = \text{exogenous}, \tag{24}$$

$$CAT_t = NDD. \tag{25}$$

Finally, the delivery delay for the sector's output, or average residence time of an order in the backlog, is given by the ratio of backlog to production. The backlog of unfilled orders accumulates orders less shipments (production). The order rate is exogenous. Capital acquisition time is exogenous and assumed constant. In general, the capital acquisition time will vary according to the capacity of the suppliers relative to the supply line, but the sector is assumed to be small relative to the total demand for capital and unable by itself to influence availability.

The parameter values assumed for the analysis are summarized in table 1. The parameters were chosen to represent a producer of capital goods. The parameters are consistent with survey and econometric evidence reported in various studies. The sensitivity of the model to parameters is analyzed below.

[18]Growth expectations would have to be included in a more complete model of demand forecasting, and would add amplification.

Table 1

Base case parameters.

Symbol	Definition	Value (years)
ALC	Average life of capital	20
COR	Capital/output ratio	3
NDD	Normal delivery delay	1.5
CAT	Capital acquisition time	1.5
TAB	Time to adjust backlog	1.5
TAO	Time to average orders	2
TAC	Time to adjust capital	3
TASL	Time to adjust supply line	3

Sources/Comments

ALC	Coen (1975) found service lives ranging from 8 to 22 years for equipment and 2(to 50 years for structures. Sterman (1981) estimated a 20-year lifetime for the aggregate of plant and equipment.
COR	The mean value of real private capital stock/real GNP (1958 \$) from 1946 to 19' =2.9. (Historical Statistics of the U.S. Series F-470/F-32.)
NDD and *CAT*	Mayer (1960) found mean lead times for plant and equipment (planning to completion) of 22 months (5 months planning and 17 months ordering and construction delays). Since the sector represents a capital producer, $CAT=NDD$
TAB	*TAB* should be comparable to *NDD*: Firms would not want to try to adjust backlogs faster than products can be delivered; but $TAB \gg NDD$ implies a sluggish response to abnormal delivery delays. Senge (1978), using non-durable manufacturing data, found no statistically significant difference between *NDD* ai *TAB*.
TAO	*TAO* should be greater than *TAB* to reflect the low weight managers place on current and highly uncertain orders compared to the much more certain backlo; Senge (1978) found $TAO > TAB$ (using shipments instead of orders as the measure of demand).
TAC and *TASL*	Senge (1978) found $TAC = 12.1$ quarters (est. std. dev. 2.2 quarters). *TASL* shoul be comparable to *TAC* so that orders in planning are weighted in the order decision as heavily as units in the productive stock. If $TASL > TAC$, overorderii results as capital on order is partially ignored; if $TASL < TAC$, orders in the supply line are counted more heavily in the investment decision than capital itse

5. Testing the model: The local rationality of the decision rules

Consistent with the principles of bounded rationality, management of th production sector is divided into several distinct decisions (productior investment, demand forecasting, etc.). The decision rules are based on simpl rules of thumb that use locally available and relatively certain informatior To test the local rationality of the decision rules, partial model tests of th production and investment decisions were performed.

5.1. Demand forecasting and backlog management

To test the local rationality of the decision rule for desired productio [eqs. (18)–(21)], the sector was subjected to a sudden, unanticipated increas in orders of five percent at the start of year one. To isolate the decision rule, it was assumed that production was determined solely by indicated production capacity *IPC*. Capacity then places no constraint on production, and the production scheduling equations become the only determinants of the sector's behavior.

The result (fig. 5) is a smooth and orderly response. Immediately after the shock, expected orders and production are unchanged. Backlog begins to rise. As it rises, however, firms recognize the growing discrepancy between the backlog and the backlog consistent with the normal delivery delay. Production is adjusted above expected orders by exactly enough to keep delivery delay constant. Expected orders rise as management comes to believe the new level of demand will persist, gradually shifting the burden of adjustment from the correction from backlog to the demand forecast.[19] The response is extremely rational in several senses. It is appropriate: in equilibrium, expected output, output and backlog have all expanded by five percent. It is orderly: expected orders, production and backlog all approach their new equilibrium values smoothly. Despite an unanticipated change in

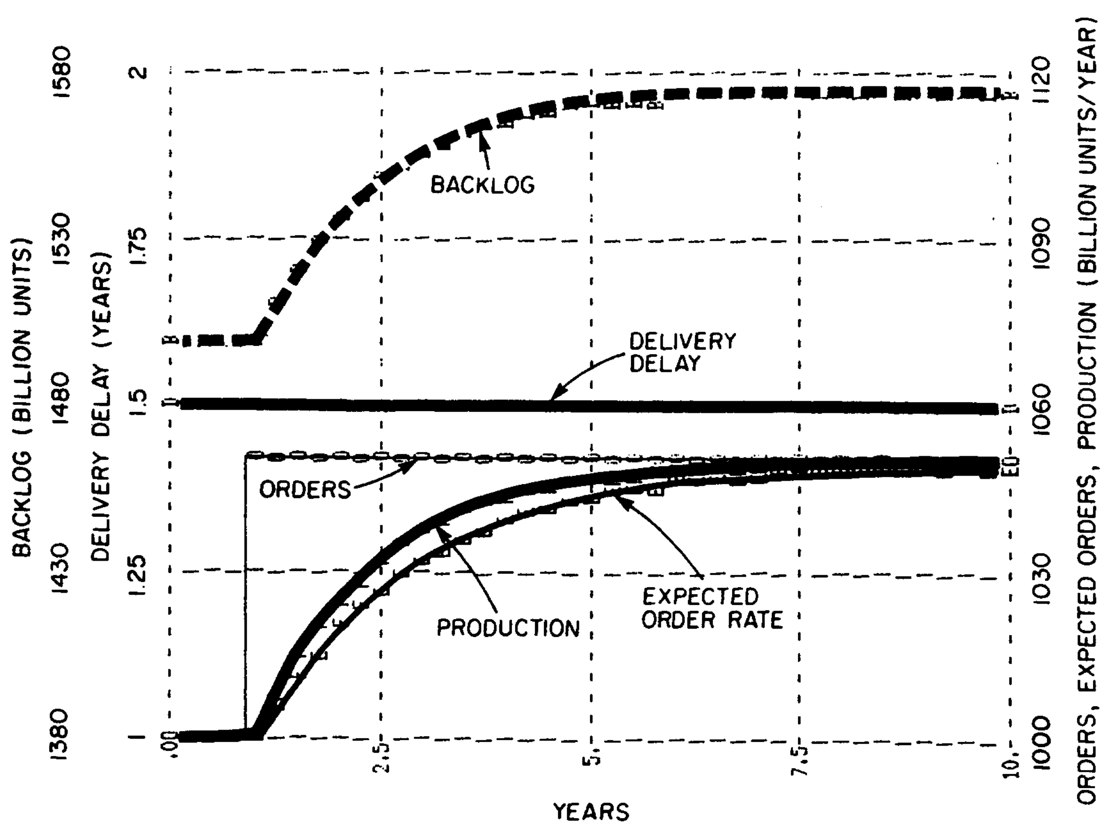

Fig. 5. Response of production scheduling subsector to step in orders.

[19]The equations for indicated production capacity (18)–(20) reduce to $IPC = EO + CB = EO + (B - IB)/TAB = EO + (B - EO*NDD)/TAB = EO[1 - (NDD/TAB)] + B/TAB$. The base case assumes $TAB = NDD$, so $IPC = B/TAB = B/NDD$, thus *IPC* always equals the production rate consistent with *NDD*, which is why *DD* remains constant in the test.

demand, the decision rule for production scheduling allows the firm to meet the higher volume of orders without upsetting its delivery schedule in the slightest.

5.2. Investment and capacity acquisition

The local rationality of the investment decision [eqs. (5)–(17)] is tested by assuming that indicated production capacity *IPC* is exogenous. The sector is subjected to a sudden, unanticipated increase in indicated production capacity of five percent in year one.

Again, the response (fig. 6) is smooth and orderly. Immediately after the shock there is a maximum discrepancy between desired and actual capital. Orders for capital rise to a peak. The supply line begins to rise. Orders drop as the supply line fills, for even though the capital stock does not increase immediately, the units ordered but not yet received are taken into account when placing future orders. Overordering, an obvious source of instability, is thus prevented. As the supply line rises, so too do acquisitions, which peak two years after the shock. As capital increases, the burden of investment shifts back to replacements. In equilibrium the desired and actual stock are again equal (likewise the desired and actual supply line). Like the production scheduling equations, the response is quite rational: the adjustment is appropriate, orderly, and essentially completed (over 95%) within twelve years.

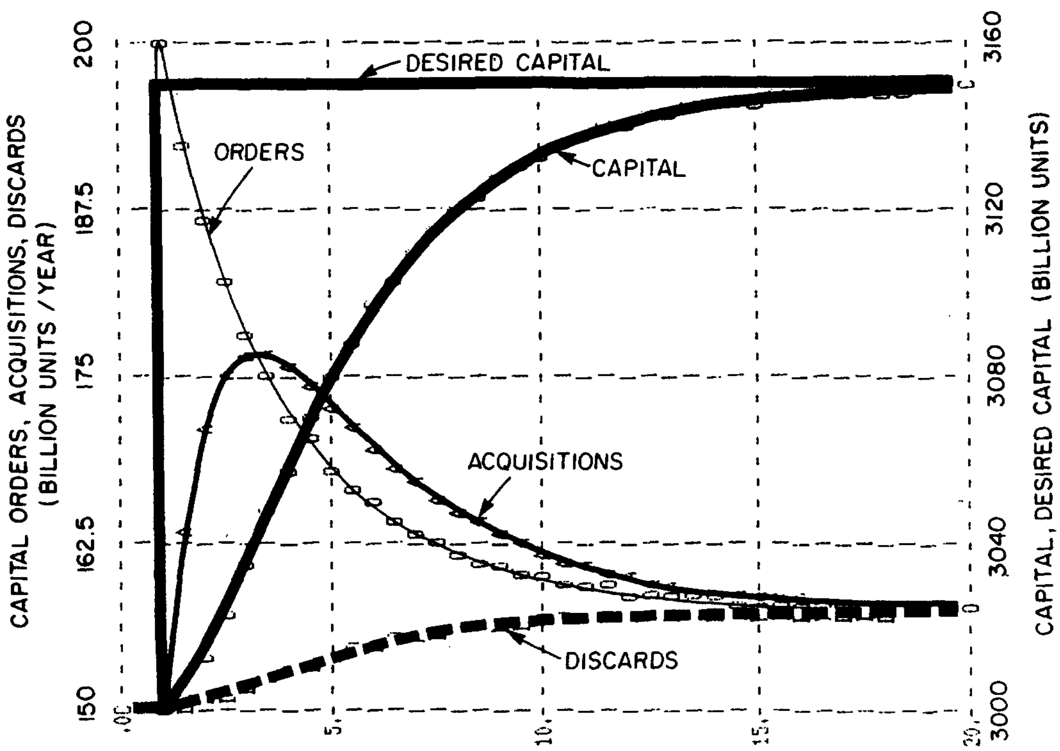

Fig. 6. Response of investment subsector to step in desired capital.

5.3. Testing the complete production sector

The partial model tests show that the individual decision rules respond rationally to unanticipated shocks. To examine the interaction of these decision rules, the entire production sector was subjected to an unanticipated increase in orders of five percent at the start of year one.

The result (fig. 7) is a highly damped oscillation with a period of about twenty years. In contrast to the previous tests, production and capacity now overshoot orders, then undershoot slightly before reaching equilibrium. Because capacity (and production) lag behind orders, the backlog and delivery delay must rise. When production equals orders (in year six) backlog stops increasing and reaches its maximum. Delivery delay peaks slightly earlier. In order to reduce the delivery delay to normal levels, production and capacity must expand above orders. By year eight, delivery delay is once again normal, but capacity still rises as capital ordered when capacity was inadequate continues to arrive. Production remains above equilibrium because the industry is reluctant to reduce utilization. By year ten, backlog has fallen enough to begin to force utilization down, but output continues to exceed orders. Delivery delay falls below normal as firms draw down their backlogs to preserve profitability. Faced with excess capacity, investment is cut back, and capacity begins to decline by year twelve. For delivery delay to return to normal, the backlog must rise, forcing output and capacity below orders. But when delivery delay has returned to normal, capacity is once again insufficient, triggering a second, though much smaller, overshoot.

The test shows that as the complexity of the system grows relative to the simplifying assumptions and decision rules used by the subsectors of the organization, the rationality of the organization's response to change is degraded. Yet despite the overshoot, the system's response is, on the whole, still rather rational. The majority of the behavior is a direct consequence of the physical constraints facing the firms in the sector. Since production must lag behind orders, backlogs must initially rise. Therefore, output and capacity must exceed orders to bring backlog back down. Overshoot is an inevitable consequence of the lags in expanding output. Oscillation, however, is not. The oscillation is a consequence of the aggressiveness with which the sector attempts to correct perceived imbalances and the sector's preference for full capacity utilization. Still, the system exhibits a high degree of damping (93% of the cycle is damped each period). And though output rises to a peak 65% greater than the change in orders, rising delivery delays are arrested within four years, production settles within 2% of its equilibrium value after fifteen years, and utilization never drops below 97%. The behavior represents a good compromise between a speedy response and stability.[20]

[20]The 20-year cycle is consistent with earlier models of capital investment and empirical work on construction or Kuznets cycles. See Forrester (1982), Low (1980) and Mass (1975) for models of Kuznets-type cycles arising out of capital-investment policies. For empirical work on Kuznets cycles see, e.g., Hickman (1963) and Kuznets (1930).

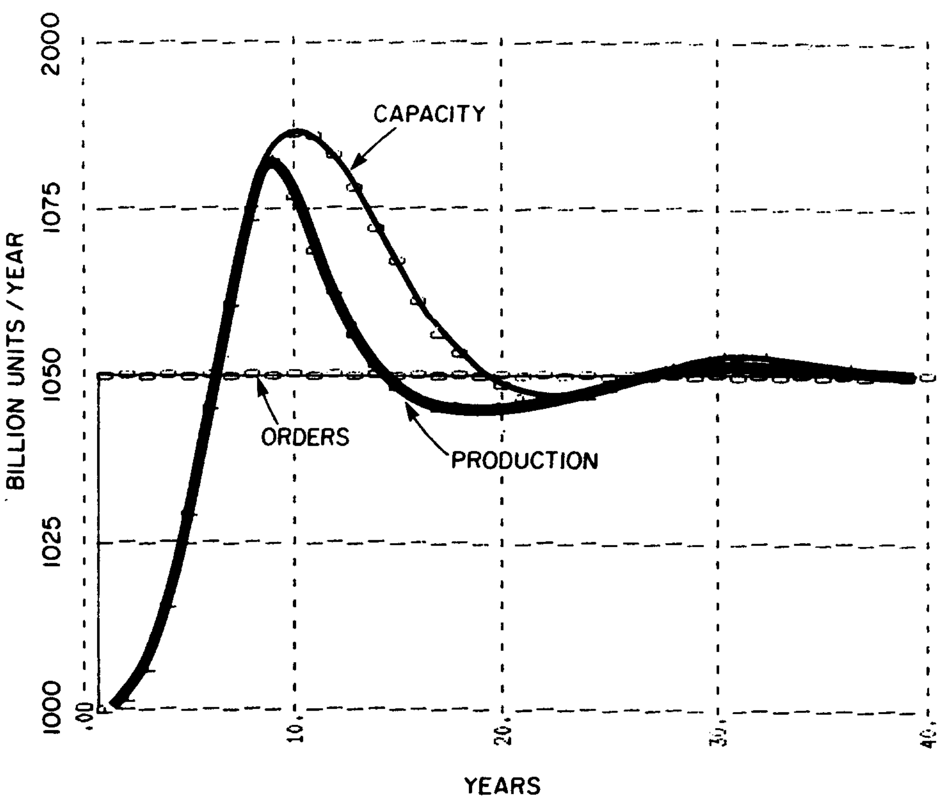

Fig. 7a. Response of production sector to step in orders: Output and capacity.

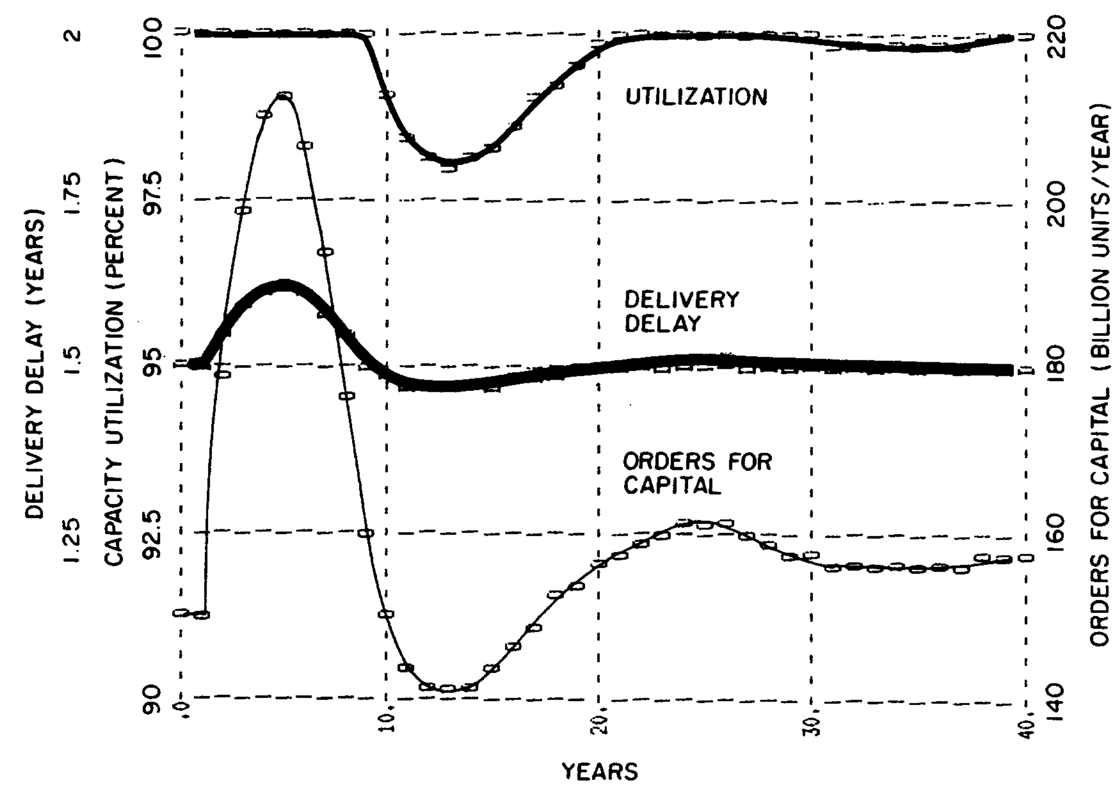

Fig. 7b. Response of production sector to step in orders: Utilization, delivery delay, and capital orders.

6. Testing the dynamic hypothesis

To test the self-ordering hypothesis, the production sector is used to represent the capital-producing sector of the aggregate economy.[21] The total demand for capital is now composed of two parts, an exogenous order rate for capital deriving from the goods sector of the economy (all non-capital industries) and the self-ordering component (the capital sector's own orders for capital). The backlog of the capital sector becomes the sum of the supply lines of the goods and capital sectors. The supply line of the goods sector accumulates that sector's orders for capital less goods-sector acquisitions. A direct consequence of self-ordering is that the capital acquisition time faced by the capital sector is the time required to produce its own output. In addition, it is assumed that each order in the backlog has an equal probability of being filled. Consequently, the output of the capital sector is divided between the goods and capital sectors in proportion to their supply lines, implying the priority of the two sectors is equal.

The model was subjected to an unanticipated increase in orders for capital from the goods sector of one percent. The response (fig. 8) is a large-amplitude limit cycle with a steady-state period of 49 years. Fig. 9 shows one complete cycle drawn from the steady-state region of fig. 8. The gross qualitative features of the behavior correspond to the long wave produced by the full National Model:

(1) The cycle has a period substantially longer than the business or Kuznets cycle and more than double the period of the production sector in isolation without self-ordering.
(2) Output rises slowly as capital is accumulated but falls precipitously, followed by a long depression while the excess capital depreciates. Capital peaks after output.
(3) Delivery delay peaks before the peak of output.
(4) The cycle is a limit cycle that persists without continuous exogenous triggering.

[21]The following equations are added or modified to implement the test:

$$B_t = GSL_t + SL_t, \tag{23'}$$

$$OR_t = GCO_t + CO_t, \tag{24'}$$

$$CAT_t = DD_t, \tag{25'}$$

$$GSL_t = \int_{t_0}^{t} (GOR_t - GCA_t)\,dt + GSL_{t_0}, \tag{26}$$

$$GCA_t = GSL_t / CAT_t, \tag{27}$$

$$GCO_t = \text{exogenous}, \tag{28}$$

where GOR = goods sector, capital order rate (units/year), GSL = goods sector, supply line of unfilled orders (units), GCA = goods sector, capital acquisition rate (units/years).

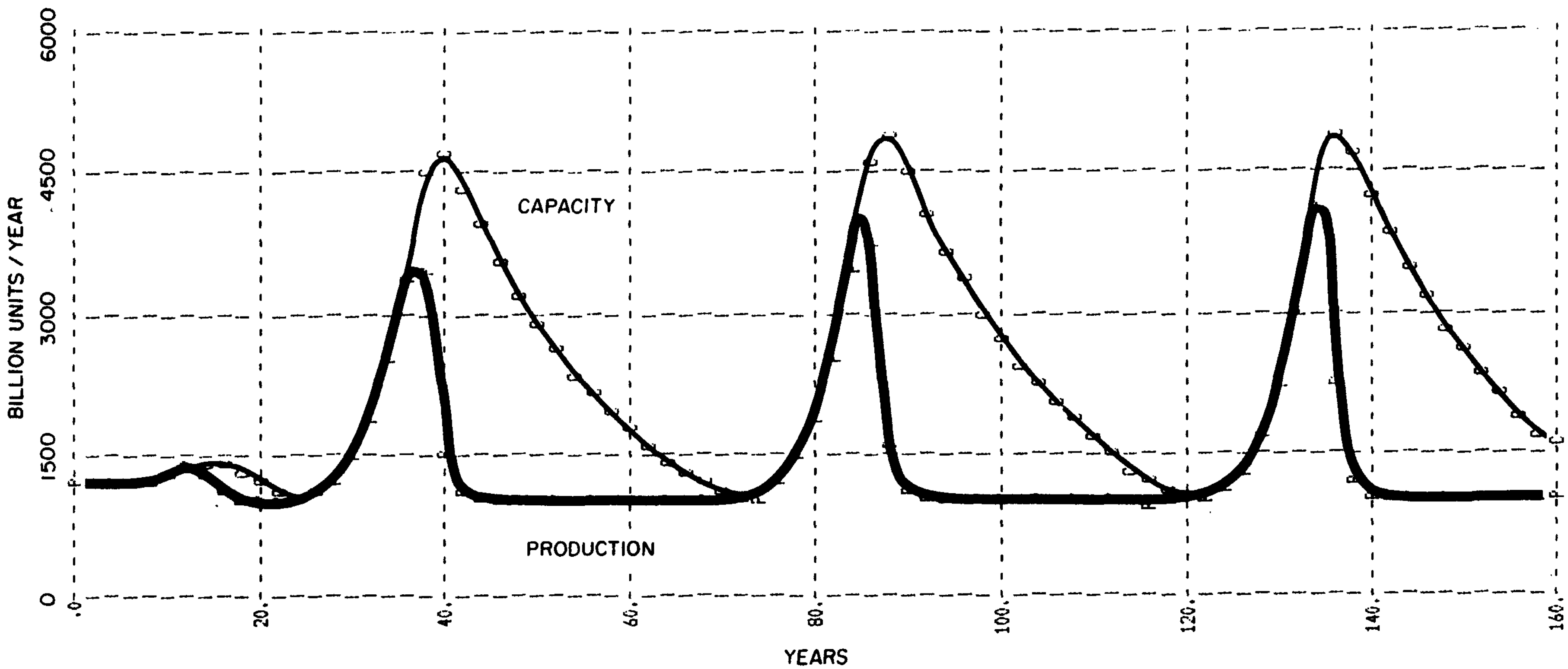

Fig. 8. Long wave resulting from self-ordering.

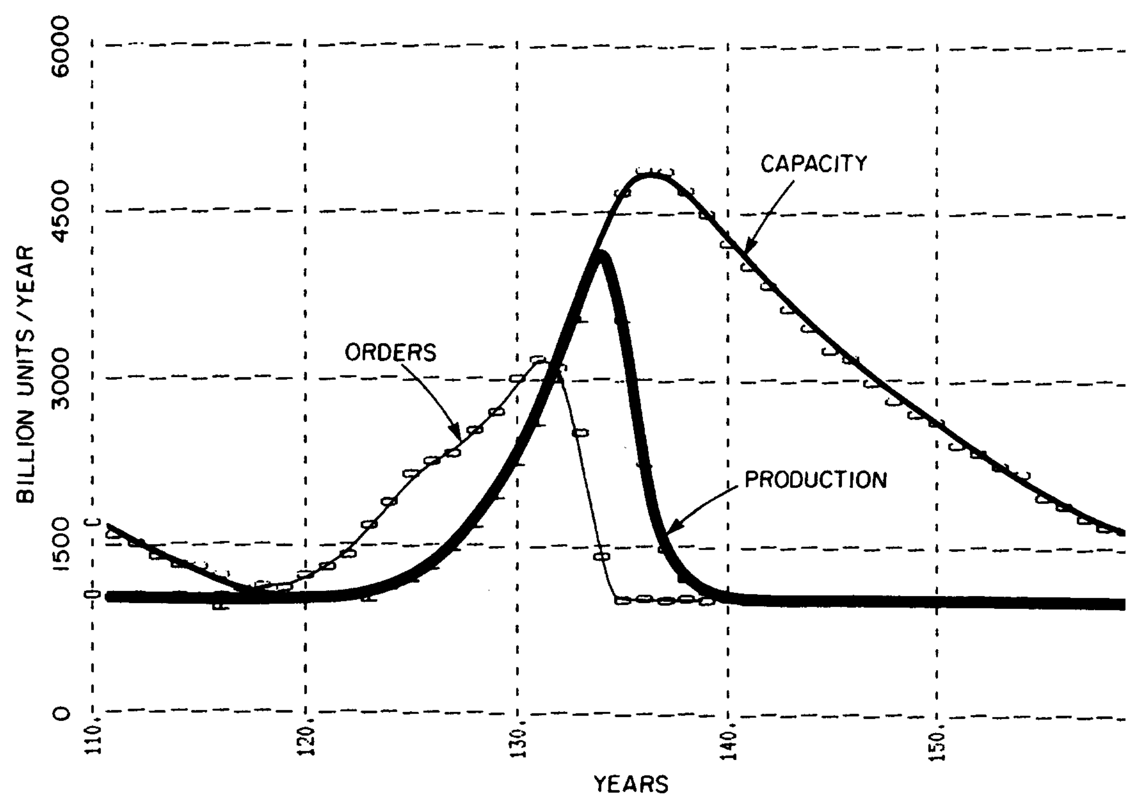

Fig. 9a. Long wave: Orders, production, and capacity.

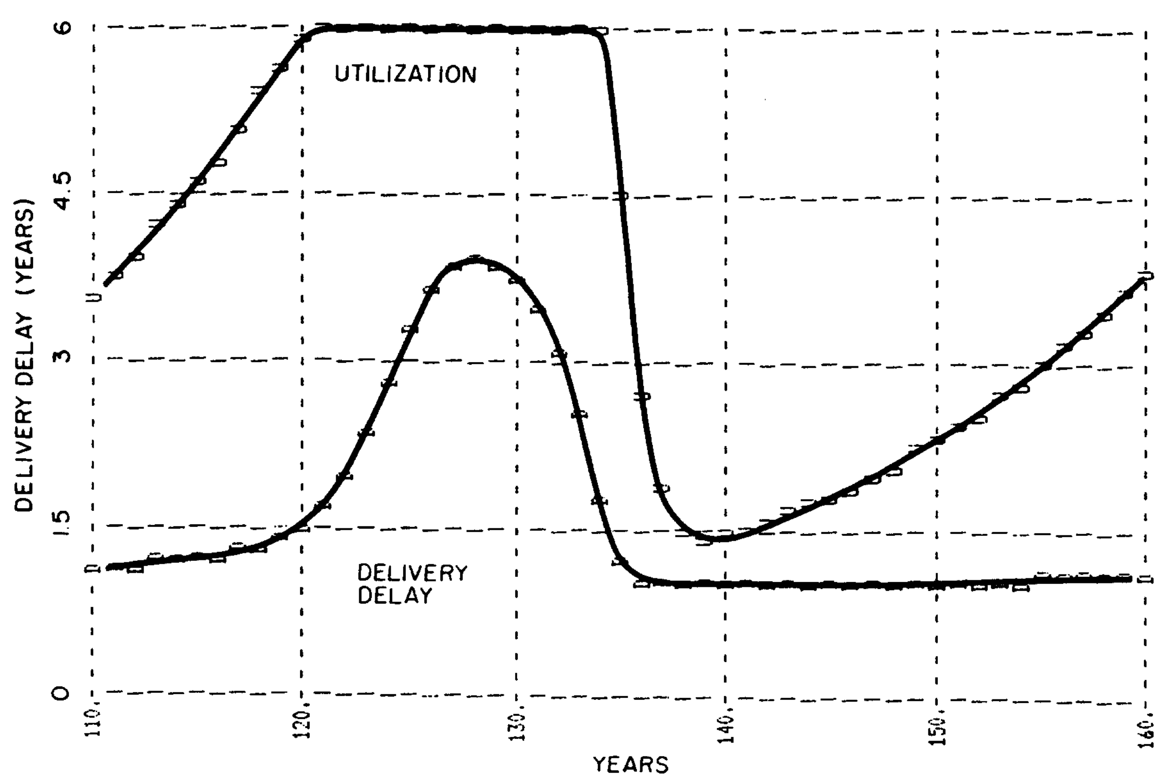

Fig. 9b. Long wave: Delivery delay and capacity utilization.

To clarify the sources of the behavior, consider the sequence of events shown in fig. 9. In the 110th year, the capital sector has excess capacity and is producing primarily for the goods sector. Net investment in the capital sector is negative. Capacity is falling. In approximately the 118th year, capacity and orders become equal, but because backlog and delivery delay are below normal, output remains depressed. By year 120, capacity and output become equal and delivery delay becomes normal. However, the sector is not in equilibrium because capacity has fallen below orders.

Unlike the response of the sector in isolation, capacity and output do not then rise smoothly to equilibrium, but continue to expand well beyond the equilibrium level of output. Self-ordering is directly responsible, through several channels. First, net investment in the capital sector is negative due to excess capacity until year 118. As capacity falls towards orders, orders for capital rise to the replacement level. Acquisitions, however, lag behind by the capital acquisition time. As a result, capacity falls below orders, and delivery delay rises above normal. Additional orders are placed to correct this discrepancy, swelling the backlog of the sector, increasing desired output and causing still more orders for capital. This most basic of the self-ordering loops is the inevitable consequence of the fact that capital is an input to its own production. As orders for capital are placed in an attempt to reduce the discrepancy between demand and capacity, self-ordering acts to increase the discrepancy by expanding desired production with each new order. The sector chases its own shadow.

Second, because capacity is inadequate, delivery delay rises above normal. As capital producers attempt to expand, they find capital acquisitions lagging further behind orders. Capacity expands less rapidly than anticipated, widening the gap between desired and actual capital, causing still more orders to be placed and further lengthening the delivery delay. Third, faced with lengthening lead times, capital producers attempt to compensate by ordering further ahead, allowing orders to expand still further.

As a consequence, though output begins to grow rapidly, demand grows more rapidly, and the delivery delay rises. Within eight years capital acquisitions have expanded enough to allow capacity to gain ground on demand. By the 128th year, output is expanding as fast as orders, and delivery delay reaches its maximum value. The sector's output now rapidly begins to catch up to orders, though orders, through self-ordering, continue to rise. By the 132nd year, output overtakes orders and backlog reaches its peak. Delivery delay is now falling, reducing orders by accelerating acquisitions and reducing the required supply line. But though orders are now falling, backlog and delivery delay remain well above normal, forcing capacity to expand further. By the 134th year, delivery delay and backlog have returned to normal, but capacity is much higher than its equilibrium level.

With output at record levels and orders plummeting, backlog and delivery delay reach and then drop below their normal values as firms attempt to maintain full utilization. The backlog is rapidly depleted, however, and output drops precipitously. The sector enters a period of depression with capacity far in excess of demand. Note that capacity continues to rise even after output has fallen. Though the sector's orders for capital peak in year 131, capital already ordered continues to arrive, worsening overcapacity.[22]

With its backlog depleted and capacity utilization at 25%, the sector cuts gross investment to zero by year 139. Output and gross investment remain depressed for the next two decades as capacity slowly depreciates, until capacity once again equals orders and the cycle begins again.

7. Analyzing the long wave

7.1. Comment on the realism of the behavior

The long wave generated by the model closely resembles, in qualitative terms, the long wave generated by the National Model. But the magnitude of the fluctuation is extreme: delivery delay expands to over 250% of normal, capacity utilization falls to less than 25%, total gross investment falls by over 75% from the peak with investment in the capital sector collapsing to zero. In comparison, between 1929 and 1933, U.S. real private investment fell 88%, real GNP fell by 30%, and unemployment reached 25%.

The extreme simplicity of the model is the cause of the extreme behavior. Since only the most basic channels for self-ordering are represented, the full burden of the disequilibrium pressures generated during the cycle must be borne by a few variables. Extensions to the present model as well as the full National Model show that as additional structure and realism are added, the burden borne by any individual channel falls while the total amplification, to a first approximation, stays the same. For example, the model excludes relative prices. In reality, as orders outstrip capacity, the price of capital rises, easing some of the pressure on delivery delay. At the same time, higher capital prices would boost profits, encouraging expansion and reinforcing self-ordering.

7.2. The role of self-ordering: Parameter sensitivity

The strength of self-ordering in equilibrium is governed primarily by the capital/output ratio. As calculated in eq. (i), the equilibrium multiplier effect created by self-ordering is given by $1/(1-COR/ALC)$. Reducing the capital/output ratio should diminish both the amplitude and period of the

[22] A recent example of capacity overshoot is provided by the commercial construction industry [*Business Week* (4 Oct. 1982, pp. 94–98)].

cycle by reducing the magnitude of the capacity overshoot and hence the time required for capacity to depreciate. Table 2 shows period, amplitude and damping as a function of *COR* given the other parameters of the model. When $COR \approx 0$, self-ordering is eliminated, and the behavior approaches that of the sector in isolation with a period of twenty years and a damping ratio of 93%. As *COR* rises, damping falls dramatically while the period remains relatively constant. At $COR \approx 1.6$, damping is eliminated and the oscillation reaches a fixed steady-state amplitude. Increasing *COR* then rapidly lengthens the period and boosts the amplitude. The results verify the crucial role of self-ordering in lengthening the natural period of the accelerator mechanism portrayed in the production sector.

Table 2
Sensitivity to capital/output ratio.

COR (years)	Period (years)	'Damping ratio'[a]	Steady-state amplitude[b] (% of base)
0	20	0.93	0
0.1	20	0.88	0
0.5	20	0.79	0
1.0	20	0.59	0
1.6	20	≈0	1
2.0	23	NA	20
2.5	34	NA	40
3.0 (Base case)	49	NA	100
3.5	55	NA	140
4.0	60	NA	150

[a]'Damping ratio' $= 1 -$ peak of cycle n/peak of cycle $n-1$ (measured with respect to equilibrium values).
[b]Measured in production rate.

The strength of self-ordering is also determined by the average life of capital *ALC*. Altering *ALC* has two opposing effects. On the one hand, *ALC* controls the time required for excess capacity to depreciate during the depression phase, so shortening *ALC* should reduce the period. But shortening *ALC* also increases the strength of self-ordering, suggesting a larger amplitude. Table 3 shows that the amplitude is increased substantially as *ALC* falls. The period, however, is quite insensitive to *ALC* and, in fact, tends to shrink as *ALC* gets shorter *or* longer. Though a shorter *ALC* implies faster decay of excess capacity, more rapid depreciation makes it more difficult for the capital sector to catch up to orders during the expansion phase. Output overtakes demand at a later and higher level, so even though excess capacity is eliminated more rapidly, more excess capacity is generated, reducing the period only six years when *ALC* is cut from twenty to ten years. Similarly, a longer *ALC* extends the time required to eliminate

Table 3

Sensitivity to average life of capital.

ALC (years)	Period (years)	Steady-state amplitude[a] (% of base)
10	43	170
15	45	120
20 (Base case)	49	100
30	49	50
40	35	20

[a]Measured in production rate *PR*.

excess capacity but reduces the strength of self-ordering so that output overtakes orders at a much lower level. The results, particularly the reduction in period with longer *ALC*, show the period of the cycle to be determined primarily by the strength of the self-ordering loop and not the life of capital. The insensitivity to *ALC* shows the cycle is not created by the echo effect that figures in some explanations of the long wave.[23]

Self-ordering also operates through other channels. During the upswing of the cycle, rising delivery delays slow capital acquisition, further augmenting the backlog and lengthening lead times. To test the importance of this channel, it was assumed that the capital sector has absolute priority over the goods sector when demand for capital exceeds capacity, and is always able to receive capital within the normal delivery delay,

$$CA_t = SL_t / NDD, \tag{7'}$$

$$GCA_t = PR_t - CA_t. \tag{26'}$$

The result is a 37-year cycle with an amplitude 70% as large as the base case. The qualitative features are largely unchanged. With priority over other sectors, the capital sector can catch up to orders sooner and at a lower level. But it is unlikely that such allocation exists. All firms, to some extent, are involved in purchasing from each other. Capital producers do not know the extent to which their customers are coupled through self-ordering and certainly do not consult an input/output table to assign priorities on the basis of the technical coefficients of their customers. The assumption of equal priorities is probably roughly correct in the aggregate, at least for an approximately competitive economy.[24]

[23]Both Kondratiev and De Wolff invoked the echo effect to explain the period of the long wave [Van Duijn (1983, pp. 62, 67)].

[24]The allocation issue raises the fascinating question of whether a centrally planned economy could minimize or eliminate the long wave through careful allocation of investment and output. Empirical evidence is inconclusive, and analysis is made difficult by entrainment of market and centrally planned economies through trade.

Self-ordering also operates through the backlog correction (fig. 2). The aggressiveness with which firms seek to maintain delivery delays at normal levels is controlled by the time to adjust backlog TAB. As shown in table 4, the period and amplitude are inversely related to TAB. While the amplitude is quite sensitive to TAB, the period is relatively less so.

Table 4

Sensitivity to aggressiveness of backlog adjustment.

TAB (years)	Period (years)	Steady-state Amplitude[a] (% of base)
0.5	55	130
1.0	53	120
1.5 (Base case)	49	100
2.0	39	60
2.5	30	30

[a]Measured in production rate PR.

Likewise, more aggressive adjustment of capital to desired levels (table 5) lengthens the period and increases the amplitude by boosting orders even further above base-case levels for a given discrepancy between desired and actual capital. Again the variation in the period is less than the variation in the amplitude.

Table 5

Sensitivity to aggressiveness of capital stock adjustment.

TAC (years)	Period (years)	Steady-state amplitude[a] (% of base)
1.5	56	150
2	54	120
3 (Base case)	49	100
4	37	40
5	31	20

[a]Measured in production rate.

Speeding adjustment of the supply line, in contrast, is stabilizing (table 6). Since the capital and supply line corrections oppose each other, more aggressive adjustment of the supply line relative to the capital stock effectively reduces the strength of self-ordering. Eliminating the supply line correction altogether means capital on order is ignored, destabilizing the system by causing overordering, as can be verified in simulations without self-ordering.

Table 6

Sensitivity to aggressiveness of supply-line correction.

TASL (years)	Period (years)	Steady-state amplitude[a] (% of base)
1.5	34	40
2	42	70
3 (Base case)	49	100
4	51	110
∞	57	140

[a]Measured in production rate.

As shown in fig. 3, rising delivery delay boosts the desired supply line, adding still more to orders during the expansion phase. To test the importance of this channel, eq. (14) was modified so that the desired supply line is always based on the normal delivery delay, eliminating the hoarding phenomenon described by T. W. Mitchell,

$$PCAT_t = NDD. \tag{14'}$$

The result is a cycle with the same period and an amplitude (measured in output) 90% as large. The timing and character of the behavior are virtually unaffected. Therefore, the decision rule for the desired supply line, though contributing some amplification, does not appear to play a strong role in the long wave.

7.3. *The role of non-linearity*

The limit cycle behavior of the model implies one or more non-linearities bound what would otherwise be an expanding oscillation. Two obvious non-linearities are the limitation on orders as a fraction of capacity [eq. (10)], intended to capture bottlenecks and other constraints on the rate of expansion, and the diminishing returns to capital [eq. (16)]. Eliminating both non-linearities by setting

$$COF_t = ICOF_t \quad \text{for} \quad ICOF_t > 0.05, \tag{10'}$$

$$DC_t = IC_t \tag{16'}$$

yields a period of 75 years and an amplitude nearly 3.5 times greater than the base case.[25] The test clearly shows constraints on either the level or rate

[25]Eliminating only one of the non-linearities simply allows the system to grow further until the remaining constraint becomes binding.

of capital expansion to be important factors in bounding the period and amplitude of the cycle. However, without these non-linearities the cycle still reaches a finite steady-state amplitude, suggesting another non-linearity is primarily responsible for bounding the oscillation. That non-linearity is the capacity utilization formulation [eq. (2)].

In both figs. 7 and 9, output falls below capacity when the backlog drops below a level consistent with the normal delivery delay, restraining the overshoot of output and preventing the backlog from declining too far below its equilibrium value. If output were always equal to capacity, backlog would decline further below its equilibrium value, forcing larger cutbacks in investment and destabilizing the cycle. To illustrate, setting

$$PR_t = PC_t \tag{1'}$$

without self-ordering leaves the period largely unaffected but reduces the damping ratio from 93% to 35%. When self-ordering is added, eq. (1′) results in an expanding oscillation which soon drives backlog, delivery delay and capital acquisitions below zero. As further confirmation of the importance of capacity utilization, the full model was simulated with

$$PR_t = IP_t \tag{1''}$$

implying perfectly flexible capacity. The result is a highly damped response with a single overshoot of capacity above its equilibrium value.

Thus the crucial non-linearity is the capacity utilization policy. Constraints on the rate or level of capacity expansion may limit the period and amplitude of the cycle. But fundamentally it is the fact that output can only rise as capacity grows that creates the disequilibrium, and the fact that output must fall as the backlog is depleted that limits it.[26]

8. Conclusions

The results show that the dynamic hypothesis of self-ordering is sufficient to cause a long wave, given only the physical structure of capital

[26]Though the behavior of the model is dominated by non-linearity, analysis of the eigenvalues of the linearized system verified the crucial role of capacity utilization in controlling damping. Linearizing around the initial equilibrium with eq. (1′) ($CU=1$) yields dominant eigenvalues corresponding to expanding oscillation with a period of 25.5 years and a growth rate of the envelope of 29%/year. In contrast, linearization with eq. (1″) ($CU=IP/PC$) yielded eigenvalues corresponding to a highly damped oscillation with a period of 23.8 years and a decay rate of the envelope of 19%/year. Intuitively, the slope of CU determines the relative strengths of the oscillatory capital acquisition loop and the stable first-order production scheduling loop. During the expansion phase, utilization is at its maximum, and the unstable loop dominates. As excess capacity develops, CU falls, and dominance shifts to the stable loop, limiting the amplitude of the cycle.

accumulation and the local rationality of the decision rules. More precisely, the results show that self-ordering amplifies the disequilibrium pressures created by the interaction of locally rational decision rules with the lags in expanding capacity, verifying Forrester's statement (1977, p. 534) that self-ordering 'creates the 50-year cycle out of what would otherwise be a 20-year medium cycle in capital acquisition'.

The decision rules portrayed in the model are consistent with the information-processing capabilities of economic agents. The individual decision rules are locally or intendedly rational. Yet as the complexity of the environment grows, the overall rationality of the system's response is degraded. The results demonstrate what Simon (1947, p. 81) calls

> '"segments" of rationality... [the] behavior shows rational organization within each segment, but the segments themselves have no very strong interconnections.'

The positive feedback loops created by self-ordering increase the amplitude and lengthen the period of oscillations caused by the production and investment policies of the sector, which, from the vantage point of the firm, are quite rational. Indeed, an individual firm cannot distinguish orders that are part of the 'true' long-run demand from the 'false' orders generated by amplification and self-ordering. A firm or management team that tried to turn away orders or expand less aggressively on the grounds that it would cause overexpansion in twenty years would not last long in the face of high delivery delays and rapid growth.

The model shows that only the most fundamental feedback loops created by self-ordering are necessary to generate a robust long wave. But the sufficiency of the basic self-ordering channels does not mean other mechanisms are unimportant or irrelevant. Self-ordering also creates feedback channels through, for example, labor markets, growth expectations, prices, financial markets, and aggregate demand. These are portrayed in the full National Model. Adding these additional mechanisms does not change the basic character of the long wave, but adds 'fine structure' to the behavior, reduces the sensitivity to individual parameters, and permits realistic policy analysis.

The results should not be interpreted as excluding other mechanisms as amplifying or contributory factors in the long wave. However, those who would argue for the primacy of other mechanisms should demonstrate the sufficiency of those mechanisms in a framework that permits reproducible testing. In particular, the model shows the long wave can arise with technology held completely constant (without even the technological changes implicit in varying the mix of capital and labor). The results suggest that the historical long-wave pattern in innovations is the result of entrainment by the physical process of self-ordering rather than vice-versa, as explained by Forrester (1977) and by Graham and Senge (1980). If the 'long-wave theory of innovation' more nearly describes the situation than the 'innovation theory of the long wave' favored by the neo-Schumpeterian school, policies directed at stimulating innovation may be insufficient to mitigate the effects of the current long-wave downturn.[27]

These issues have important policy implications, and it is hoped that the methodological framework illustrated with the simple model presented here can provide the common ground for systematic exploration of the forces behind the long wave, contributing to an integrated theory of disequilibrium economic behavior.

Appendix 1: Additional amplifying mechanisms in the long wave

The basic self-ordering loops analyzed above are not the only source of amplification in the long wave. Other sources of amplification that operate in the National Model include growth expectations — the spread of optimism and pessimism — as described by Wesley Mitchell (1941, p. 5):

> 'Virtually all business problems involve elements that are not precisely known, but must be approximately estimated even for the present, and forecast still more roughly for the future.... This fact gives hopeful or despondent moods a large share in shaping business decisions.... Most men find their spirits raised by being in optimistic company. Therefore, when the first beneficiaries of a trade revival develop a cheerful frame of mind about the business outlook, they become centers of infection, and start an epidemic of optimism.'

To the extent expectations of future growth lead to expansion of investment, self-ordering ensures the demand for capital will in fact rise, validating and strengthening the forecast of continued growth.

Interactions with the labor market further strengthen self-ordering. To boost output, the capital sector expands employment as well as its capital stock. As the pool of unemployed is drawn down, the labor market tightens and wages rise. Scarcity of skilled workers and higher labor costs encourage the substitution of capital for labor throughout the economy, further augmenting the demand for capital. Thus one would expect labor and capital to expand together in the early phases of the long wave, followed by a period of stagnant employment but continued growth in capital and output. Such patterns emerge from simulations of the National Model and have been documented for both the U.S., Europe, and Japan [Graham and Senge (1980), Senge (1982), Freeman (1979) and Freeman et al. (1982)].

[27]Both Freeman et al. (1982) and Van Duijn (1983) argue for stimulus of innovation as prime components of an effective strategy to counter the long wave. While renewed commitment to R&D is needed, these results suggest dealing with excess physical capacity may be more important [Mass and Senge (1981), Sterman (1983b)].

Still more amplification is due to interactions with the financial markets. During the expansion phase of the long wave, rising capital demand boosts prices. Inflation in capital prices implies the real interest rate on capital investment declines, encouraging further investment, and leading to still more pressure on prices. Debt builds up. During the long wave downturn, falling demand for capital softens prices, leading to an increase in real interest rates, further cuts in investment, and still more deflationary pressure. A debt–deflation spiral [Fisher (1933)] may then result as debtors find their cash flows squeezed by declining demand and falling prices. Historically, long wave expansions have indeed been periods of low or negative real interest rates, especially near the end of the expansion. Near the peaks, real interest rates have risen sharply and remained at high levels through the downturns and into the depression periods [Senge (1983)].

Additional amplification arises from the familiar consumption multiplier: the expansion of the capital sector's output and employment boosts aggregate income, which feeds back to further stimulate investment demand by augmenting the demand for consumer goods and housing.

Interactions between self-ordering and innovation, international trade and political values also exist and may further amplify the long wave (see footnote 7).

Appendix 2: Equations for simulation

```
0120 NOTE  CAPITAL SECTOR
0130 NOTE
0140 A     KPR.K=KSPR*KPC.K*KCU.K+(1-KSPR)*KIPC.K
0150 A     KCU.K=TABHL(KCUT,KIP.K/KPC.K,0,2.0,.2)
0160 T     KCUT=0/.3/.55/.75/.9/1/1/1/1/1/1
0170 A     KIP.K=KB.K/KNDD
0180 A     KPC.K=KC.K/KCOR
0190 L     KC.K=KC.J+(DT)(KCA.J-KCD.J)
0200 A     KCD.K=KC.K/KALC
0210 A     KCA.K=KSCA*(KSL.K/KCAT.K)+(1-KSCA)(KSL.K/KNDD)
0220 L     KSL.K=KSL.J+(DT)(KCO.J-KCA.J)
0230 A     KCO.K=KC.K*KCOF.K
0240 A     KCOF.K=TABXT(KCOFT,KICOF.K,-.1,.4,.05)
0250 T     KCOFT=0/0/.02/.05/.1/.15/.2/.25/.28/.3/.3
0260 A     KICOF.K=(KCD.K+KCC.K+KCSL.K)/KC.K
0270 A     KCSL.K=(KDSL.K-KSL.K)/KTASL
0280 A     KDSL.K=KPCAT.K*KCD.K
0290 A     KPCAT.K=KNCAT*KEDDSL.K
0300 A     KEDDSL.K=TABXT(KTPCAT,KCAT.K/KNCAT,0,3,.5)
0310 T     KTPCAT=0/.5/1/1.5/2/2.5/3
0320 A     KCC.K=(KDC.K-KC.K)/KTAC
0330 A     KDC.K=KRC*KRDRC.K
0340 A     KRDRC.K=TABXT(KTRDRC,KIC.K/KRC,-.5,7.5,.5)
0350 T     KTRDRC=0/0/.5/1/1.5/2/2.5/3/3.5/4/4.5/5/5.4/5.7/5.9/6/6
0360 A     KIC.K=KSDC*KIPC.K*KCOR+(1-KSDC)*KXDC.K
0370 A     KIPC.K=KEO.K+KCB.K
0380 A     KCB.K=(KB.K-KIB.K)/KTAB
```

```
0390 A      KIB.K=KNDD*KEO.K
0400 L      KEO.K=KEO.J+(DT/KTAO)(KOR.J-KEO.J)
0410 NOTE
0420 NOTE   PARAMETERS AND INITIAL VALUES
0430 NOTE
0440 C      KNDD=1.5
0450 C      KCOR=3
0460 C      KALC=20
0470 C      KTASL=3
0480 C      KTAC=3
0490 C      KTAB=1.5
0500 C      KTAO=2
0510 C      KSPR=1
0520 C      KSCA=1
0530 C      KSDC=1
0540 N      KNCAT=KNDD
0550 N      KDD=KNDD
0560 N      KRC=KC
0570 N      KPR=KPC
0580 N      KC=(1-KSSO)*GCO*KCOR+KSSO*GCO*KCOR*KALC/(KALC-KCOR)
0590 N      KSL=KCAT*KCD
0600 N      KEO=KPC
0610 NOTE
0620 NOTE   COUPLING EQUATIONS
0630 NOTE
0640 A      KOR.K=GCO.K+KSSO*KCO.K
0650 A      KB.K=GSL.K+KSSO*KSL.K
0660 A      KCAT.K=KSSO*KDD.K+(1-KSSO)*KNDD
0670 A      KDD.K=KB.K/KPR.K
0680 C      KSSO=1
0690 A      KXDC.K=KRC*(1+STEP(KFIDC,KTIDC))
0700 C      KFIDC=.05
0710 C      KTIDC=1
0720 NOTE
0730 NOTE   GOODS SECTOR
0740 NOTE
0750 L      GSL.K=GSL.J+(DT)(GCO.J-GCA.J)
0760 N      GSL=GCAT*GCO
0770 A      GCA.K=KSCA*(GSL.K/GCAT.K)+(1-KSCA)(KPR.K-KCA.K)
0780 A      GCAT.K=KDD.K
0790 A      GCO.K=GRCO*(1+STEP(GFICO,GTICO))
0800 C      GRCO=1E12
0810 C      GFICO=.05
0820 C      GTICO=1
0830 NOTE
0840 NOTE   SIMULATION CONTROL PARAMETERS
0850 NOTE
0860 SPEC   DT=.0625/LENGTH=0
0870 A      PLTPER.K=PLTP1+STEP(PLTP2-PLTP1,PLTIME)
0880 C      PLTP1=0
0890 C      PLTP2=2.5
0900 C      PLTIME=1000
0910 A      PRTPER.K=PRTP1+STEP(PRTP2-PRTP1,PRTIME)
0920 C      PRTP1=0
0930 C      PRTP2=0
0940 C      PRTIME=1000
0950 PLOT   KOR=O,KPR=P,KPC=C/KDD=D/KCU=U(0,1)
0960 RUN
0970 C LENGTH=10
0980 C PLTP1=.25
0990 C KSSO=0
1000 C KSPR=0
```

```
1010 PLOT KOR=0,KEO=E,KPR=P(1E12,1.12E12)/KB=B(1380E9,1580E9)/KDD=D(1,2)
1020 RUN FIGURE 5
1030 C LENGTH=20
1040 C PLTP1=.5
1050 C KSSO=0
1060 C KSDC=0
1070 PLOT KC=C,KIC=I(3E12,3.16E12)/KCO=0,KCA=A,KCD=D(150E9,200E9)
1080 RUN FIGURE 6
1090 C LENGTH=40
1100 C PLTP1=1
1110 C KSSO=0
1120 PLOT KOR=0,KPR=P,KPC=C(1E12,1.1E12)
1130 PLOT KCO=0(140E9,220E9)/KDD=D(1,2)/KCU=U(.9,1)
1140 RUN FIGURE 7
1150 C LENGTH=200
1160 C GFICO=.01
1170 PLOT KPR=P,KPC=C(0,6E12)
1180 RUN FIGURE 8
1190 C LENGTH=160
1200 C PLTIME=110
1210 C PLTP2=1
1220 C GFICO=.01
1230 PLOT KOR=0,KPR=P,KPC=C(0,6E12)
1240 PLOT KDD=D(0,6)/KCU=U(0,1)
1250 RUN FIGURE 9
```

DEFINITIONS

SYMBOL	TYPE	DEFINITION
DT	S	SOLUTION INTERVAL (YEARS)
GCA	A	GOODS SECTOR, CAPITAL ACQUISITIONS (UNITS/YEAR)
GCAT	A	GOODS SECTOR, CAPITAL ACQUISITION TIME (YEARS)
GCO	A	GOODS SECTOR, CAPITAL ORDERS (UNITS/YEAR)
GFICO	C	GOODS SECTOR, FRACTIONAL INCREASE IN CAPITAL ORDERS (FRACTION)
GRCO	C	GOODS SECTOR, REFERENCE CAPITAL ORDERS (UNITS/YEAR)
GSL	L N	GOODS SECTOR, SUPPLY LINE (UNITS)
GTICO	C	GOODS SECTOR, TIME TO INCREASE CAPITAL ORDERS (YEAR)
KALC	C	CAPITAL SECTOR, AVARAGE LIFE OF CAPITAL (YEARS)
KB	A	CAPITAL SECTOR, BACKLOG (UNITS)
KC	L N	CAPITAL SECTOR, CAPITAL STOCK (UNITS)
KCA	A	CAPITAL SECTOR, CAPITAL ACQUISITIONS (UNITS/YEAR)
KCAT	A	CAPITAL SECTOR, CAPITAL ACQUISITION TIME (YEARS)
KCB	A	CAPITAL SECTOR, CORRECTION FOR BACKLOG (UNITS/YEAR)
KCC	A	CAPITAL SECTOR, CORRECTION FOR CAPITAL (UNITS/YEAR)
KCD	A	CAPITAL SECTOR, CAPITAL DISCARDS (UNITS/YEAR)
KCO	A	CAPITAL SECTOR, CAPITAL ORDERS (UNITS/YEAR)
KCOF	A	CAPITAL SECTOR, CAPITAL ORDER FRACTION (FRACTION)
KCOFT	T	CAPITAL SECTOR, CAPITAL ORDER FRACTION TABLE
KCOR	C	CAPITAL SECTOR, CAPITAL OUTPUT RATIO (YEARS)
KCSL	A	CAPITAL SECTOR, CORRECTION FOR SUPPLY LINE (UNITS/YEAR)
KCU	A	CAPITAL SECTOR, CAPACITY UTILIZATION (FRACTION)
KCUT	T	CAPITAL SECTOR, CAPACITY UTILIZATION TABLE
KDC	A	CAPITAL SECTOR, DESIRED CAPITAL (UNITS)
KDD	A N	CAPITAL SECTOR, DELIVERY DELAY (YEARS)
KDSL	A	CAPITAL SECTOR, DESIRED SUPPLY LINE (UNITS)

KEDDSL	A	CAPITAL SECTOR, EFFECT OF DELIVERY DELAY ON SUPPLY LINE (DIMENSIONLESS)
KEO	L N	CAPITAL SECTOR, EXPECTED ORDERS (UNITS/YEAR)
KFIDC	C	CAPITAL SECTOR, FRACTIONAL INCREASE IN DESIRED CAPITAL (FRACTION)
KIB	A	CAPITAL SECTOR, INDICATED BACKLOG (UNITS)
KIC	A	CAPITAL SECTOR, INDICATED CAPITAL (UNITS)
KICOF	A	CAPITAL SECTOR, INDICATED CAPITAL ORDER FRACTION (FRACTION)
KIP	A	CAPITAL SECTOR, INDICATED PRODUCTION (UNITS/YEAR)
KIPC	A	CAPITAL SECTOR, INDICATED PRODUCTION CAPACITY (UNITS/YEAR)
KNCAT	N	CAPITAL SECTOR, NORMAL CAPITAL ACQUISITION TIME (YEARS)
KNDD	C	CAPITAL SECTOR, NORMAL DELIVERY DELAY (YEARS)
KOR	A	CAPITAL SECTOR, ORDER RATE (UNITS/YEAR)
KPC	A	CAPITAL SECTOR, PRODUCTION CAPACITY (UNITS/YEAR)
KPCAT	A	CAPITAL SECTOR, PERCEIVED CAPITAL ACQUISITION TIME (YEARS)
KPR	A N	CAPITAL SECTOR, PRODUCTION RATE (UNITS/YEAR)
KRC	N	CAPITAL SECTOR, REFERENCE CAPITAL (UNITS)
KRDRC	A	CAPITAL SECTOR, RATIO OF DESIRED TO REFERENCE CAPITAL (DIMENSIONLESS)
KSCA	C	CAPITAL SECTOR, SWITCH FOR CAPITAL ACQUISITIONS (DIMENSIONLESS)
KSDC	C	CAPITAL SECTOR, SWITCH FOR DESIRED CAPITAL (DIMENSIONLESS)
KSL	L N	CAPITAL SECTOR, SUPPLY LINE (UNITS)
KSPR	C	CAPITAL SECTOR, SWITCH FOR PRODUCTION (DIMENSIONLESS)
KSSO	C	CAPITAL SECTOR, SWITCH FOR SELF ORDERING (DIMENSIONLESS)
KTAB	C	CAPITAL SECTOR, TIME TO ADJUST BACKLOG (YEARS)
KTAC	C	CAPITAL SECTOR, TIME TO ADJUST CAPITAL (YEARS)
KTAO	C	CAPITAL SECTOR, TIME TO AVERAGE ORDERS (YEARS)
KTASL	C	CAPITAL SECTOR, TIME TO ADJUST SUPPLY LINE (YEARS)
KTIDC	C	CAPITAL SECTOR, TIME TO INCREASE DESIRED CAPITAL (YEAR)
KTPCAT	T	CAPITAL SECTOR, TABLE FOR PERCEIVED CAPITAL ACQUISITION TIME
KTRDRC	T	CAPITAL SECTOR, TABLE FOR RATIO OF DESIRED TO REFERENCE CAPITAL
KXDC	A	CAPITAL SECTOR, EXOGENOUS DESIRED CAPITAL (UNITS)
LENGTH	S	SIMULATION LENGTH (YEARS)
PLTIME	C	PLOT START TIME (YEAR)
PLTPER	A	PLOT PERIOD (YEARS)
PLTP1	C	PLOT PERIOD 1 (YEARS)
PLTP2	C	PLOT PERIOD 2 (YEARS)
PRTIME	C	PRINT START TIME (YEAR)
PRTPER	A	PRINT PERIOD (YEARS)
PRTP1	C	PRINT PERIOD 1 (YEARS)
PRTP2	C	PRINT PERIOD 2 (YEARS)
STEP		STEP FUNCTION
TABHL		FUNCTION FOR NONLINEAR RELATIONSHIP
TABXT		FUNCTION FOR NONLINEAR RELATIONSHIP

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